

The 2009-2012 Ionosonde and IRI2012 Variability of $foF2$, $hmF2$, $M3000F2$, $B0$, $B1$ Parameters over Warsaw

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Abstract

This paper presents comparisons of variability and accordance of ionospheric parameters $foF2$, $hmF2$, $M3000F2$, $B0$, $B1$ over the middle latitude station in Warsaw (52.21°N, 21.06°E). Examination included observational data from Space Research Centre ionosonde in Poland and International Reference Ionosphere (IRI) 2012 model, for the time period of increasing solar activity from 2009 to 2012. The analysis concerned: trend, monthly median differences in twenty-four hours variability, local minima and maxima. Results are presented as tables of semi-annual data, and plots of difference in four-year period. The study indicated good agreement of $foF2$ and $hmF2$ parameters. Underestimations of $B1$ and $M3000F2$, variability of $B0$ parameter in Bil-2000, Gul-1987, and ABT-2009 option, were taken into consideration.

Key words: ionosonde, IRI, ionospheric sounding.

1. INTRODUCTION

Ionospheric soundings in Poland started in Warsaw in the 1960s, and are continued currently by VISRC2 ionosonde of the Plasma Physics Department in the Space Research Centre in Warsaw. Position of the station (geographical coordinates 52.21°N, 21.06°E; geomagnetic coordinates 50.51°N,

105.70°E) situates it as a middle latitude one, with solar events characteristic for this region (SRC PAS 2014).

The data obtained from ionosonde was processed by Autoscala software designed for automatic scaling of the main ionospheric characteristics from ionograms, based on an image recognition technique. At the moment of publishing this paper, Autoscala gives an output of the following ionospheric characteristics: $foF2$, $MUF(3000)F2$, $(3000)F2$, $foF1$, $h'Es$, $ftEs$, and the estimation of the bottom vertical electron density profile from the base of the ionosphere up to the maximum electron density $NmF2$ (INGV 2014).

In this paper, observational data of the ionosphere were compared to modeled characteristics by URSI IRI model, for days during the period 2009-2012. The international reference ionosphere (IRI) is the international standard for the specification of ionospheric densities and temperatures. It was developed and is being updated by a joint working group of the International Union of Radio Science (URSI) and the Committee on Space Research (COSPAR). As an empirical model, IRI is based on the existing data record, and the IRI working group has been dedicated to deduce the dominant variation patterns of ionospheric parameters from this data record (Bilitza 2001, Bilitza *et al.* 2014).

The study of accordance was made for the main ionospheric parameters:

- the ordinary wave critical frequency in the F region is the most important $F2$ layer characteristic; it corresponds to the maximum radio frequency that can be reflected at vertical incidence,
- the minimum virtual height of the ordinary wave $hmF2$ characterizes the highest stratification in the $F2$ region,
- the $M(3000)F2$ is related to Maximum Usable Frequency for 3000 km path length,
- $B0$ describes the thickness of the bottom side profile,
- $B1$ determines the shape of the profile between $hmF2$ and $h0:24$, which is the height where the electron density drops to $0.24NmF2$.

The description of the $F2$ critical frequency can be done by IRI using two methods: CCIR and URSI. Both are based on the first Fourier analysis with 15 coefficients and seventh order of the monthly median ionosondes diurnal variation and worldwide description in spherical functions. Propagation parameter $M(3000)F2$ is obtained from relation $foF2$ and MUF , scaled from ionograms, and CCIR numerical maps. Thus, the obtained $M(3000)F2$ factor with created correction factor (dependent on solar activity functions and frequencies of E and F layers), and solar activity functions, enable calculation of $hmF2$ parameter. URSI prefers the second option, especially at low latitudes. The $B1$ shape bottomside profile function was assumed to take values from in step-like transition 3 to 5 (Bilitza *et al.* 1990, 2014). The IRI

in actual 2012 model offers the three values of $B0$ thickness: Bil-2000, Gul-1987, and ABT-2009.

2. DESCRIPTION OF DATA SET AND METHOD OF ANALYSIS

Data used for this study was recorded by VISRC2 ionosonde located at Warsaw position. For the comparisons we used IRI 2012 with STORM correction model (Bilitza *et al.* 2014). IRI is based on ITU-R prediction of monthly median values with decile variability by linear relationship with solar activity (ITU-R 2012). Analysed data set from Warsaw ionosonde contains monthly hour median values of parameters f_oF2 , $M3000F2$ for URSI, and CCIR, h_mF2 , $B1$, $B0$ option: ABT, BIL, and GUL.

Considered time periods started in January 2009 with a low value of solar radio flux and ended in December 2012 when R parameter from January 2011 was rising through increasing sun activity in eleven-year cycle (see Fig. 1, from www.spaceweather.gc.ca database). The plot presents a comparison of daily and median sun solar radio fluxes in specified selected terms.

Results were shown as multiple plots of a 24-hour universal time variability from days in every month for 2009-2012 period of selected parameters. All considered data were presented as a median difference between the IRI values and those observed by Warsaw ionosonde, as in the equation:

$$\text{diff} = \frac{\text{IRI}_p - \text{WI}_p}{\text{IRI}_p + \text{WI}_p} \times 100\% , \quad (1)$$

where IRI_p is the selected specific monthly hour median IRI parameter and WI_p is the selected specific monthly hour median measured Warsaw Ionosonde parameter.

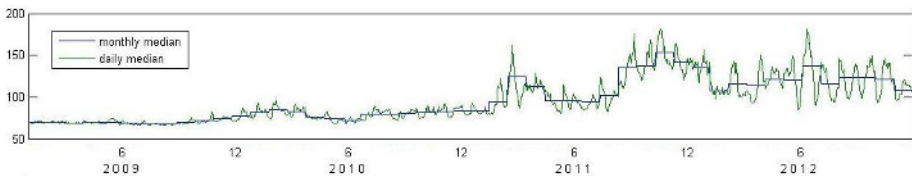


Fig. 1. 2009-2012 comparison of monthly and daily median of solar 10.7 cm flux level.

3. ANALYSIS

This paper contains analysed data presented as figures of monthly seasonal variation of parameters f_oF2 , h_mF2 , $M3000F2$, $B0$, and $B1$ at the Warsaw position. Data is plotted as a difference of IRI and the value measured by the ionosonde, as calculated according to Eq. 1. Colour bars present a difference in percent of the obtained values. The shades of grey under zero value illus-

trate degree of IRI underestimation and above an overestimation. White gaps with “NO DATA” description define the time periods where data was not available for calculations. The terms local minimum and maximum used in the work represent the calculated lowest and highest values of difference between monthly hour medians for years 2009-2012. Trend analysis refers to a comparison of an estimated parameter variability in the annual time period.

Table 1 presents summary of medians differences in 6-month ranges for the considered 2009-2012 period. The results represent Me_{diff} parameter calculated from Eq. 1. Me_{IRI} and Me_{ISD} are, respectively, the median values of the parameter from IRI model and measured by Warsaw ionosonde.

Figures 2 and 3 show monthly variation of maximum frequency of $F2$ layer for URSI and CCIR option. The values predicted by IRI models and those from the Warsaw ionosonde follow the same trend as an annual variable of parameter. Differences occur in the IRI narrower estimation of, extended to the night side part, positive growth of $foF2$ parameter. As a result of an increased solar activity (Fig. 2, years 2011-2012) varying underestimations and overestimations are visible and reduced to night in the time period of low sun activity (years 2009-2010). Generally, the median difference for URSI semi-annual analysed sections reaches values in the range of $\pm 2.5\%$, with the lowest at level -6.7% , for the start of analysed time (January-June 2009). CCIR model presents closer value in section January-June 2009 (on -3.1% level) and minimally better from July 2010 to December 2011. The minimum values of the locally observed differences for the models were -24 and -19% , the maximum values being $+16$ and $+19\%$.

Figures 4 and 5 for URSI and CCIR $hmF2$ parameter present noticeable division into the fields in which low and increased solar radio fluxes are dominant. The level of IRI difference changes from being overestimated for 2009-2010, to underestimation for 2011-2012 periods. Generally, in daytime section in figures, the IRI models in respect to Warsaw ionosonde evaluated a lower value of $hmF2$ and higher value at night from January 2009 to the end of 2010, night overestimate is dominating. The analysis suggests an agreement of trend predicted by IRI and Warsaw ionosonde; both $hmF2$ parameters present higher values at night, and in a second part of the plot (years 2011-2012), where Solar Radio flux level is increased. Noticeable differences are in Warsaw ionosonde data presenting lower value at night and day in the year 2009. Median of the semi-annual difference for all analysed sections reaches low values, from -3 to $+1\%$. The locally observed difference minima reach values from -7% to the maximum level at $+13\%$ for both models.

The predicted IRI and Warsaw-ionosonde values for $M3000F2$ follow a similar trend. The IRI model presents close results (see Table 1, part 3). In all data, the $M3000F2$ parameters are on higher level at daytime, from Au-

Table 1
2009-2012 median difference summary of ionosphere parameters in 6-month ranges

foF2 URSI								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	3,849	3,886	4,390	4,419	5,189	5,687	6,116	5,759
Me W1	4,400	3,800	4,200	4,600	5,300	5,400	6,100	5,500
Me diff [%]	-6.7	1.1	2.2	-2.0	-1.1	2.6	0.1	2.3
foF2 CCIR								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	4,135	4,034	4,616	4,541	5,320	5,678	6,003	5,772
Me W1	4,400	3,800	4,200	4,600	5,300	5,400	6,100	5,500
Me diff [%]	-3.1	3.0	4.7	-0.6	0.2	2.5	-0.8	2.4
M3000F2								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	3,142	3,161	3,103	3,123	3,007	3,010	2,952	3,012
Me W1	3,360	3,380	3,370	3,380	3,270	3,240	3,150	3,160
Me diff [%]	-3.4	-3.3	-4.1	-4.0	-4.2	-3.7	-3.2	-2.4
hmF2 CCIR								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	261	265	268	270	277	281	286	284
Me W1	258	260	268	270	288	293	303	300
Me diff [%]	0.5	0.9	0.0	0.0	-2.0	-2.1	-2.9	-2.7
hmF2 URSI								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	259	266	267	270	277	283	286	285
Me W1	258	260	268	270	288	293	303	300
Me diff [%]	0.3	1.0	-0.2	0.1	-2.0	-1.8	-2.8	-2.5
B0 Gul-1987								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	78.5	77.8	80.6	79.7	84.1	83.7	89.2	83.6
Me W1	70.0	66.0	73.0	77.0	89.0	95.0	102.0	96.0
Me diff [%]	5.7	8.2	4.9	1.7	-2.8	-6.3	-6.7	-6.9
B0 Bil-2000								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	76.2	80.3	79.4	83.8	85.1	94.5	91.8	95.9
Me W1	70.0	66.0	73.0	77.0	89.0	95.0	102.0	96.0
Me diff [%]	4.2	9.8	4.2	4.2	-2.2	-0.3	-5.3	-0.1
B0 ABT-2009								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	90.9	84.2	91.6	85.3	94.1	88.5	97.4	88.3
Me W1	70.0	66.0	73.0	77.0	89.0	95.0	102.0	96.0
Me diff [%]	13.0	12.1	11.3	5.1	2.8	-3.5	-2.3	-4.2
B1								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	1.9	2.0	1.9	2.0	1.9	2.0	1.9	2.0
Me W1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Me diff [%]	-22.4	-20.0	-22.4	-20.0	-22.4	-20.0	-22.4	-20.0
B1 ABT-2009								
	1-6.2009	7-12.2009	1-6.2010	7-12.2010	1-6.2011	7-12.2011	1-6.2012	7-12.2012
Me IRI	2.1	2.2	2.1	2.2	2.1	2.2	2.1	2.2
Me W1	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Me diff [%]	-17.6	-15.4	-17.6	-15.4	-17.6	-15.4	-17.6	-15.4

gust to April (border value of positive growths), with maximum level in the middle of specified time periods. In Warsaw ionosonde, twenty-four hour distribution presents increased borders, extending to the night-side part. Difference of *M3000F2* parameter shown in Fig. 6 presents dominating under-

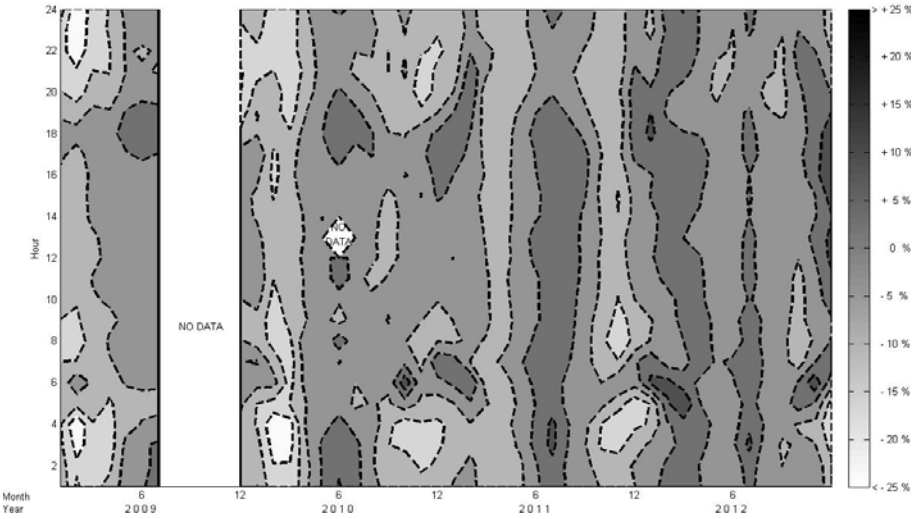


Fig. 2. 2009-2012 comparison of $foF2$ monthly median difference variation for Warsaw ionosonde and IRI 2012 URSI model.

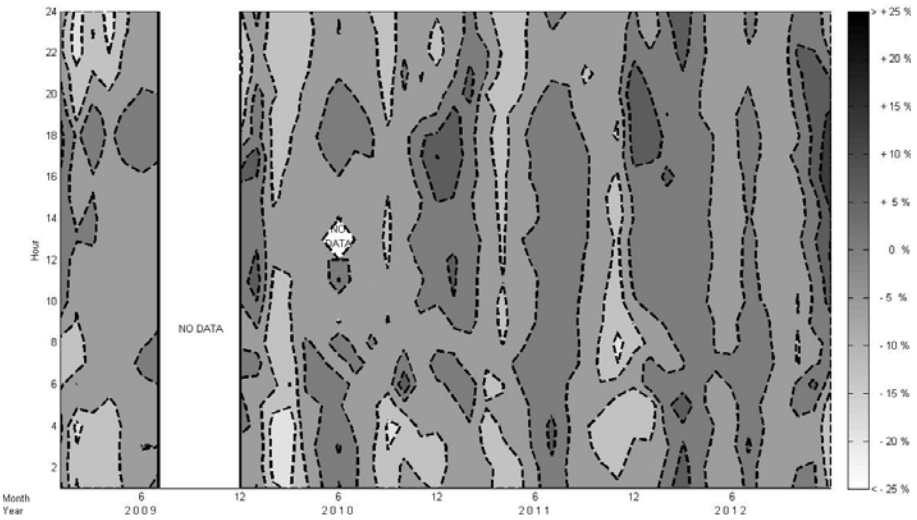


Fig. 3. 2009-2012 comparison of $foF2$ monthly median difference variation for Warsaw ionosonde and IRI 2012 CCIR model.

estimate. The highest local difference can be noticed at night part of the graph, where it reaches a local value to -9% . Positive values appear sporadically in low level, up to $+1\%$. Median difference for semi-annual analysed section reaches low-range negative values approximately at the level of

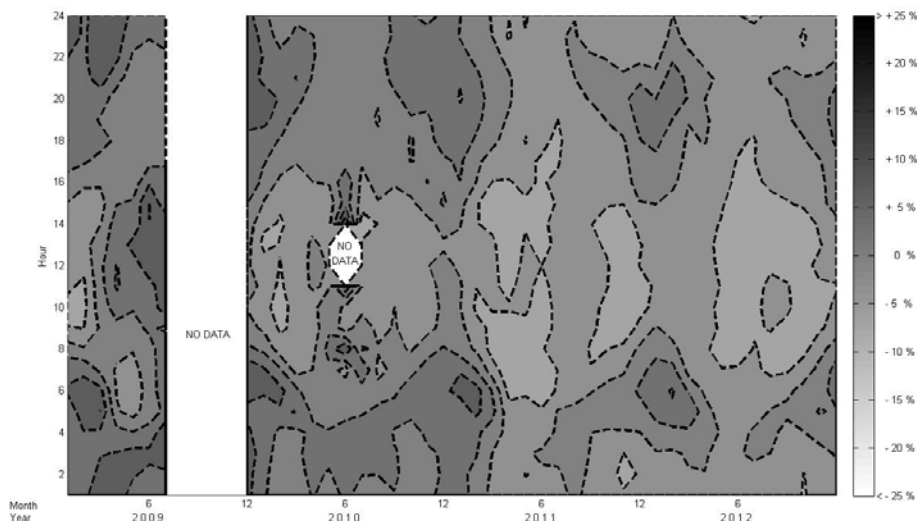


Fig. 4. 2009-2012 comparison of $hmF2$ monthly median difference variation for Warsaw ionosonde and IRI 2012 URSI model.

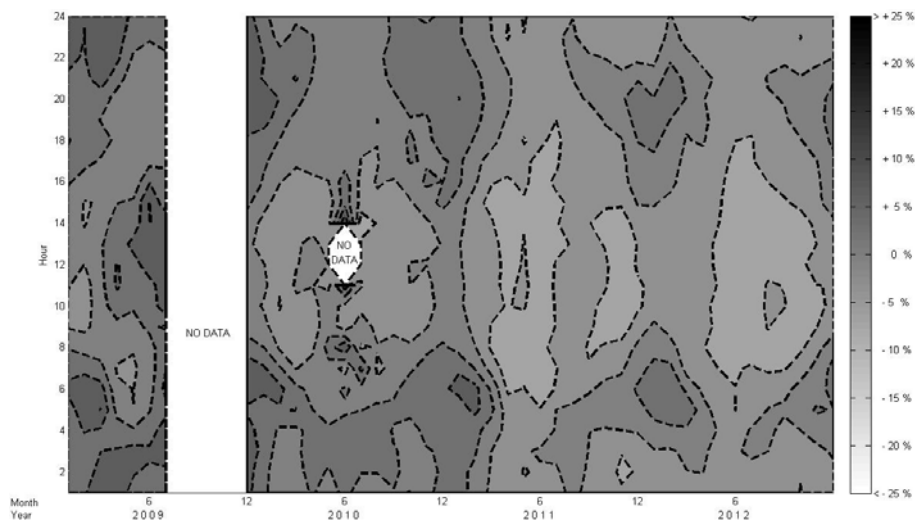


Fig. 5. 2009-2012 comparison of $hmF2$ monthly median difference variation for Warsaw ionosonde and IRI 2012 CCIR model.

−3.5%, from −2.4% for July-December 2012 to −4.2% for January-June 2011.

Difference of $B0$ parameter was presented in Fig. 7 for IRI year Gul-1987, in Fig. 8 for Bil-2000, and in Fig. 9 for a newest IRI 2012 ABT-2009 option.

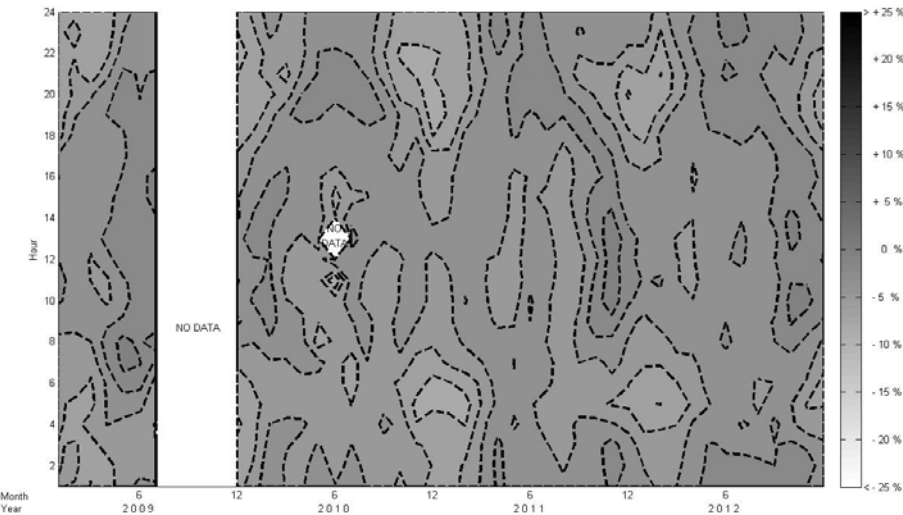


Fig. 6. 2009-2012 comparison of *M3000F2* monthly median difference variation for Warsaw ionosonde and IRI 2012 URSI model.

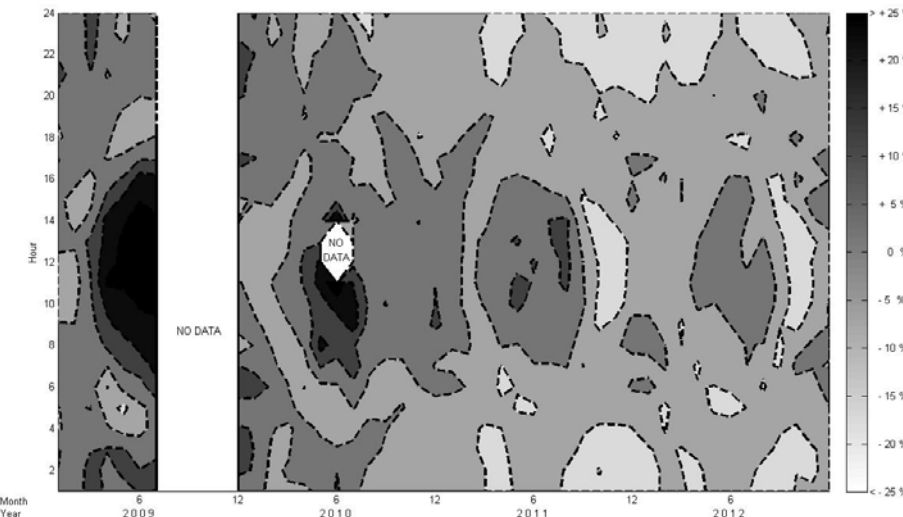


Fig. 7. 2009-2012 comparison of *B0* monthly median difference variation for Warsaw ionosonde and IRI 2012 Bil-2000 model.

Generally, the IRI models and Warsaw ionosonde follow the same trend. *B0* modelled parameters present higher values at day from months close to April-August (border value of positive growths), with maximum level close to the middle of specified time periods. Main differences are in the ABT model, evaluating longer borders extending to hours before noon than the

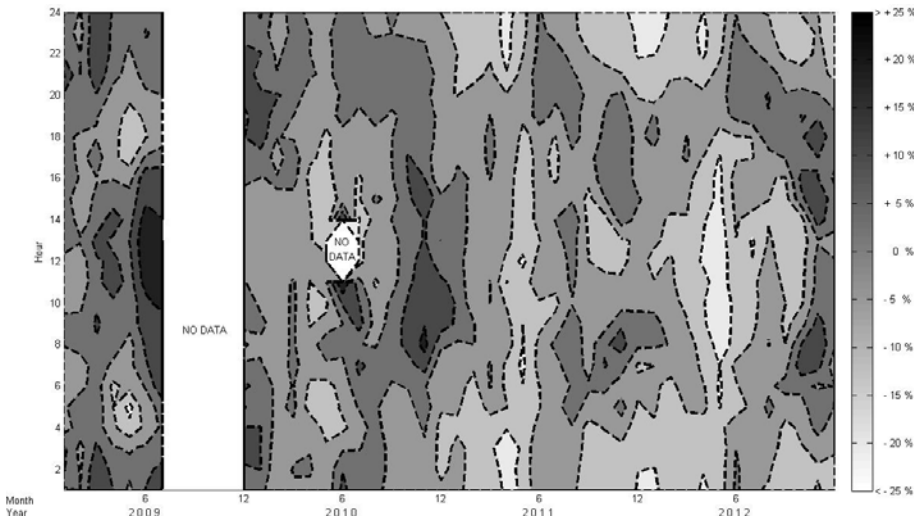


Fig. 8. 2009-2012 comparison of B_0 monthly median difference variation for Warsaw ionosonde and IRI 2012 Gul-1987 model.

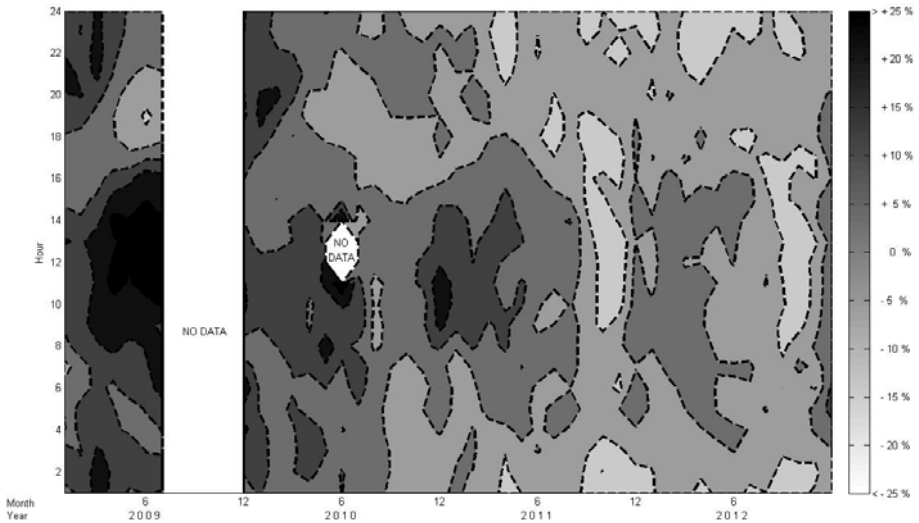


Fig. 9. 2009-2012 comparison of B_0 monthly median difference variation for Warsaw ionosonde and IRI 2012 ABT-2009 model.

Gul-1987 model, where maximum level range is shorter. Bil-2000 option presents characteristics of lower variable model in twenty-four hour distribution.

In all cases, Figs. 7-9 present noticeable division into two fields where low and increased solar radio fluxes are dominant. All models tend to over-

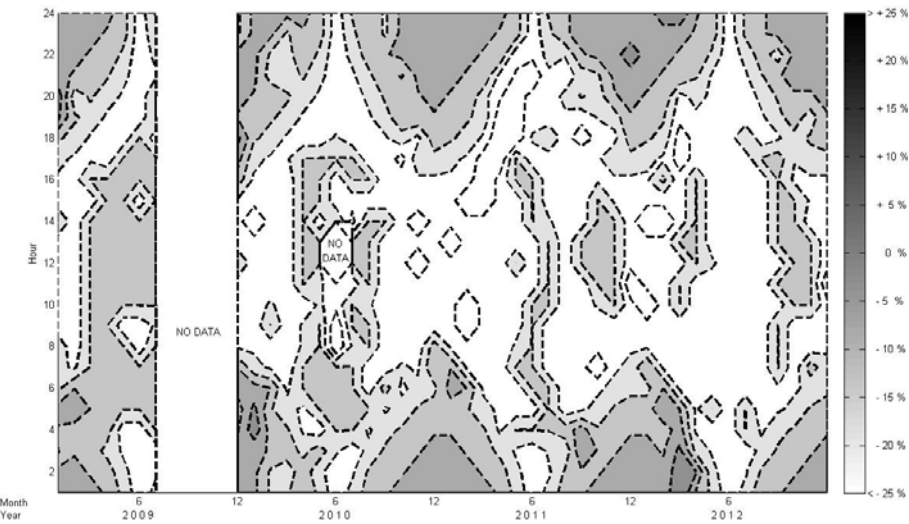


Fig. 10. 2009-2012 comparison of $B1$ monthly median difference variation for Warsaw ionosonde and IRI 2012 model.

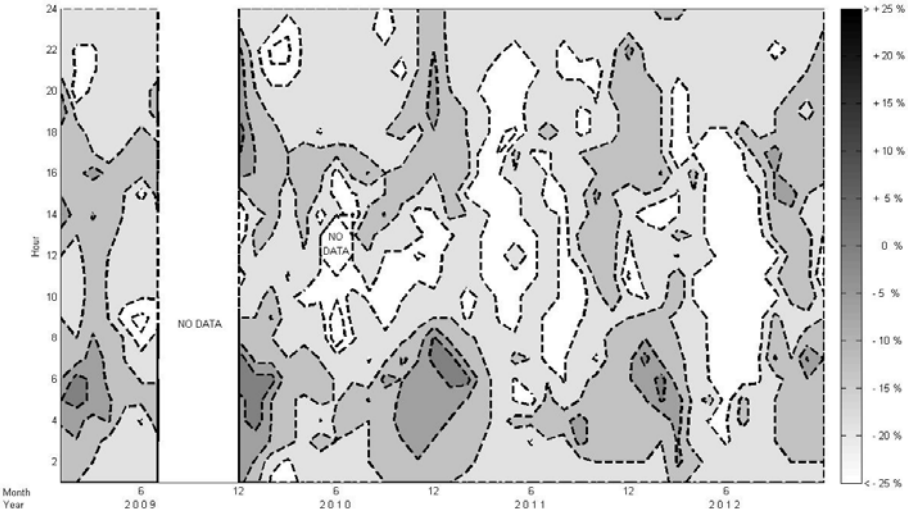


Fig. 11. 2009-2012 comparison of $B1$ monthly median difference variation for Warsaw ionosonde and IRI 2012 ABT-2009 dependent model.

estimate at the first part of graph, presenting data from January 2009 to the end of 2010, when the solar activity level is low. With increasing solar radio flux, from the beginning of 2010 to the end of year 2012, the data present noticeable underestimate.

Level of difference is summarized in Table 1 (parts 6-8). The highest level of difference in the first part of data (January 2009 – December 2010) occurs in ABT-2009 model with positive value from 5.1 to 13.0%. Gul-1987 and Bil-2000 present similar overestimate, respectively, from 1.7 to 8.2% and from 4.2 to 9.8%. In the second part of data with increased solar activity, ABT-2009 model in the first sector for the time period January-June 2011 reaches a positive value of difference, while in other models the underestimation starts to dominate. In the remaining part of graph, from July 2011 to December 2012, the level of difference take values from -2.8 to -4.2% for ABT-2009, -2.8 to -6.9% for Gul-1987, and lastly -0.1 to -5.3% for Bil-2000 option. Observed differences minima and maxima reach respectively values: Gul-1987 from -18 to +42%, Bil-2000 from -20 to +27%, ABT-2009 from -15 to +39%.

Difference of $B1$ parameter was presented in Fig. 10 for the standard model, and Fig. 11 for new $B1$, dependent on a newest IRI 2012 ABT-2009 model. Median difference values for half-year parts of data are presented in Table 1 (parts 9 and 10).

The $B1$ standard model presents trend with the highest values at night with borders of positive growth in June. In Dependent ABT-2009 this variability occurs from August to March, with extension to daytime part. While the standard model calculates one value $B1$ at the level of 1.9, outside the night borders of positive growth, the second model estimates a variable parameter during the days. Analogical variable presents trend from Warsaw ionosonde data with the lowest value at specified parts of the day.

In Figs. 10 and 11 the lowest values occur in the middle part of daytime in months close to half year. From this point, values are increasing in the direction to nighttime and winter season. IRI standard model presented in Fig. 10 reaches continuous underestimate in every part of the graph, from -20.0 to -22.4%, with local difference from -30 to +2%. $B1$ ABT-2009 also underestimates the value but in the level from -15.4 to -17.6%. For this model, the locally observed difference minimum reaches values from -32 to maximum at +6%.

4. CONCLUSIONS

Through the usage of IRI model, the monthly median values of $hmF2$, $foF2$ parameters show good agreement with Warsaw ionosonde data. Analysed differences range is on acceptable level. Generally, the variance of difference in $foF2$ parameter is a result of, presented in this paper, IRI model trend estimation at night. Similar results in differences in the CCIR and URSI options leave a choice of model to specified position and time period.

The $HmF2$ parameter presents a very close result to the data obtained from Warsaw ionosonde. Low value of the differences of medians for the

analysed semi-annual sections confirms it. Eventually, the IRI parameters in daytime part underestimations for high solar activity section, and 2009 year overestimations could be taken into consideration.

The IRI evaluated $M3000F2$ parameters show constant underestimation for all analysed time. The largest differences occurred in areas where Warsaw ionosonde day trend is extending to night side part. IRI model in twenty-four hour distribution presented a fastest decrease of $M3000F2$ parameter in time.

IRI $B0$ factors present noticeable, positive difference in dominating low-level solar radio flux, and negative in time of increasing solar activity. High level of Me_{diff} , local minimum and maximum, should be taken under consideration in examinations of that latitude region. The analysis confirmed that the preferred by CCIR Gul-1987 model is in fact the best long-term fit to parameters measured by the ionosonde. Newest ABT-2009 presents better fitting to ionosonde measured data in twenty-four hour distribution. This model for Warsaw position is a suitable alternative for time periods of increased solar activity. The IRI 2012 Bil-2000 model shows good long-term fit, the lowest value of local difference, and it is sufficient for time periods of low solar activity.

Lastly, the $B1$ parameter, with constant underestimate at the level from -20.0 to -22.4% for a standard model and from -15.4 to -17.6% for $B1$ ABT-2009, needs improvements to reduce a constant difference, which was partially done in 2009. New $B1$ ABT-2009 model noticeably follows a similar trend as the data measured by the Warsaw ionosonde, and the lowest value of median difference indicates that it should be used in the geographical position pertaining to this paper.

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